The multiple faces of working memory: Storage, processing, supervision, and coordination

Oberauer, Klaus ; Süß, H M ; Wilhelm, Oliver ; Wittmann, Werner W

Abstract: Working memory capacity was differentiated along functional and content-related facets. Twenty-four tasks were constructed to operationalize the cells of the proposed taxonomy. We tested 133 university students with the new tasks, together with six working memory marker tasks. With structural equation models, three working memory functions could be distinguished: Simultaneous storage and processing, supervision, and coordination of elements into structures. Each function was further subdivided into distinct components of variance. On the content dimension, evidence for a dissociation between verbal-numerical working memory and spatial working memory was comparatively weak.

DOI: https://doi.org/10.1016/S0160-2896(02)00115-0

Originally published at:
Oberauer, Klaus; Süß, H M; Wilhelm, Oliver; Wittmann, Werner W (2003). The multiple faces of working memory: Storage, processing, supervision, and coordination. Journal of Artificial Intelligence Research, 31(2):167-193.
DOI: https://doi.org/10.1016/S0160-2896(02)00115-0

ELSEVIER

Intelligence 31 (2003) 167–193

INTELLIGENCE

The multiple faces of working memory: Storage, processing, supervision, and coordination

Klaus Oberauer*, Heinz-Martin Süß, Oliver Wilhelm, Werner W. Wittman

University of Mannheim, Mannheim, Germany

Received 15 March 2000; received in revised form 6 July 2001; accepted 31 January 2002

Abstract

Working memory capacity was differentiated along functional and content-related facets. Twenty-four tasks were constructed to operationalize the cells of the proposed taxonomy. We tested 133 university students with the new tasks, together with six working memory marker tasks. With structural equation models, three working memory functions could be distinguished: Simultaneous storage and processing, supervision, and coordination of elements into structures. Each function was further subdivided into distinct components of variance. On the content dimension, evidence for a dissociation between verbal–numerical working memory and spatial working memory was comparatively weak.

Keywords: Working memory; Cognitive capacity; Task-set switching; Coordination

1. Introduction

Once there was a short-term store—a system responsible for the memorization of a small number of chunks for the time one needs to walk from the phone book to the telephone. Over the past three decades, this system has evolved into the central stage of higher-order cognition. Now called working memory, it has been associated with an increasing number of basic cognitive functions, up to a point where it sometimes appears as a conceptual ragbag for everything that is needed for successful reasoning, decision making, and action planning.

* Corresponding author. Allgemeine Psychologie I, Universität Potsdam, Postfach 60 15 53, 14415 Potsdam, Germany. Tel.: +49-331-977-2833.

E-mail address: ko@rz.uni-potsdam.de (K. Oberauer).

PII: S0160-2896(02)00115-0

At the same time, numerous proposals have been made to fractionate working memory, beginning with the three-component model of Baddeley (1986) and Baddeley and Hitch (1974), which continues to be differentiated into smaller units (e.g., the distinction of spatial and visual working memory by Logie, 1995, the fractionation of the central executive discussed in Baddeley, 1996). On the other hand, some authors conceptualize working memory as a global cognitive resource that establishes a common limiting factor for a large set of different tasks (e.g., Engle, Kane, & Tuholski, 1999; Just & Carpenter, 1992; Kyllonen & Christal, 1990). Typically, those pointing out fine-grained differentiations base their views on experimental work and on neuropsychological data, while those highlighting the global character of working memory mainly draw on individual difference data.

This situation raises two questions. First, what is a reasonable scope for the concept of working memory—that is, which cognitive functions should be subsumed under it? And second, to what degree is working memory unitary—that is, which level of differentiation is most adequate? We will approach these questions from an individual difference perspective. Our working definition for working memory is of a set of limiting factors for performance in complex cognitive tasks. Looking at correlations between tasks that operationalize different aspects of working memory, we investigate the associations and dissociations between several of those limiting factors. Our guiding hypothesis is that working memory, like intelligence, will ultimately be described on different levels of generality, forming a hierarchy of related constructs.

2. A facet model of working memory

We assume that working memory can be differentiated according to two dimensions or facets in the sense of facet theory (Canter, 1985; Guttman, 1954), one related to content domains, the other related to cognitive functions. On the content facet, we assume two broad categories: working memory for visuo-spatial material, and working memory for language and numerical material. This hypothesis matches the distinction of two domain-specific slave systems in Baddeley's (1986) model, and it is supported by individual differences research (Oberauer, Süß, Schulze, Wilhelm, & Wittman, 2000; Shah & Miyake, 1996) as well as brain imaging data (e.g., Smith & Jonides, 1997). On the functional facet, we distinguish three categories that together cover most of the functions attributed to working memory in the literature: simultaneous storage and processing, supervision, and coordination. Since the three functional categories are not so well established, we discuss them in more detail below.

Until recently, *simultaneous storage and processing* was the leading definition of working memory as a whole (e.g., Kyllonen and Christal, 1990, Salthouse, 1991). The concept of simultaneous storage and processing derives from the former notion of a short-term store. Daneman and Carpenter (1980) proposed to distinguish working memory from short-term memory by the addition of a processing component: Short-term memory only keeps information, working memory processes it. In order to make this differentiation meaningful, we have to adopt a narrow definition of the term *processing*, one that does not include, for example, rehearsal and grouping of items, because these processes are also involved in simple short-term memory span tasks. We propose to define *processing* as the transformation of information or the derivation of new information, in contrast to cognitive activities that maintain the information as given. Likewise, we wish to define *storage* as the retention of briefly presented new information over a period of time in which the information is no longer present. This excludes functions addressed as "long-term working memory" (Ericsson & Kintsch, 1995), which rely on well-learned structures in long-term memory, and it excludes attention to information presently perceived. It is only with these precise, narrow definitions that we can hope to distinguish "storage and processing" from other functions of the cognitive system, because under a wide definition, everything that goes on in the mind is a case of processing, and every process uses representations that must be "stored" somewhere in the cognitive system.

Supervision (also referred to as *executive processes*) involves the monitoring of ongoing cognitive processes and actions, the selective activation of relevant representations and procedures, and the suppression of irrelevant, distracting ones. Most prominently featuring in Baddeley's (1986) notion of a central executive, this family of functions is also highlighted by researchers of frontal lobes (e.g., Pennington, 1994; Stuss, Eskes, & Foster, 1994) and inhibition (Dempster, 1992; Engle, Conway, Tuholski, & Shisler, 1995; Hasher & Zacks, 1988). A recent factor-analytic study by Miyake et al. (2000) identified three factors of executive functions, interpreted as mental set shifting, inhibition of prepotent responses, and information updating. In the present study, we used task set switching, which loaded on the first of the three factors of Miyake et al., as an indicator for the supervisory function. Task set switching is regarded as one of the prototypical executive tasks (see, e.g., Meiran, 1996), because a supervisory attentional process must suppress the most active action schema (i.e., the task set used before) and select another one instead (cf. Baddeley, 1986; Shallice, 1978). Miyake et al. reported moderately high correlations between switching and other indicators of executive functioning.

As a third category, we propose the *coordination of information elements into structures*. Working memory serves to build new relations between elements and to integrate relations into structures. Take, for example, the task of interpreting a table containing a three-way interaction. One will have to compare pairs of numerical values, compare differences between pairs, and finally compare differences of differences. This requires simultaneous access to several distinct elements (in this case, numbers). The cognitive system must construct new relations between these elements, thereby establishing a mental structure on which the required response is based.

The coordinative function is prominent in the work of Halford, Wilson, and Phillips (1998), who claim that working is limited in terms of the maximum number of arguments that can be composed into a new piece of relational knowledge without blurring the distinctions between them (for similar arguments, see Robin & Holyoak, 1995). Our concept of coordination is also based on the FInst theory of Pylyshyn (1994). He argues on computational grounds that the visual system must have simultaneous access to several objects in order to build geometrical relations between them. Analogously, the reasoning system must have simultaneous access to several information elements to construct new relational knowledge. Working memory provides simultaneous access to independently varying elements by placing them in a common coordinate system. This coordinate system can be thought of as having limited capacity to hold elements and keep them separated.

A previous factor-analytic study of working memory tasks has shown that tasks measuring coordination of elements into structures were highly correlated with tasks measuring simultaneous storage and processing (Oberauer et al., 2000). Recent work by Waltz et al. (1999) has shown that patients with damage in the frontal lobes have a specific and dramatic deficit in the ability to coordinate relations in transitive inference and Raven matrix tasks. Thus, we have good reasons to include the coordination function in the scope of the concept working memory. A question that remained open so far is whether coordination forms a primary order factor separate, although related to, simultaneous storage and processing.

Conceptually, the coordination function differs from simultaneous storage and processing in several respects. First, short-term storage does not provide in itself the form of simultaneous access to elements that is necessary to construct new relations. Learning the eight numbers in a table for perfect serial recall does not bring one closer to understanding the interaction. Second, the coordination function applies not only to information that is memorized but also to information that is presently perceived. For example, when the table with the three-way interaction is visible, it is still necessary to access the numbers simultaneously in order to compute the necessary relations. Like supervision, coordination is not so much a memory function but an attentional function of working memory. Third, coordination of elements into structures does not imply that the elements are manipulated in any way. Therefore, many tasks tapping the coordination function would not obviously qualify as tasks for simultaneous storage and processing.[1]

Crossing the functional with the content facet yields a hypothetical taxonomy of working memory with six cells. Our empirical strategy was to operationalize each cell with two tasks that were specifically designed to maximize the variance due to the intended function and content categories and to minimize the contribution of the other categories. The taxonomy we propose is organized in terms of a facet structure, which implies a specific pattern of correlations between indicators of different categories (cf. Canter, 1985). Tasks in the same category on both facets should correlate higher with each other than tasks sharing only a category on one facet, which in turn should covary more than tasks from completely different categories. In terms of factor analysis, this means that each task should load on exactly two factors, one representing its functional, the other its content category.

We expected that the hypothesized factors (two content factors and three functional factors) can be separated, but will be positively correlated within each facet, because the functional and content-specific abilities differentiated on one level of generality have a

[1] Various other coordinative functions of working memory have occasionally been emphasized in various contexts in the literature. Baddeley (1996), for example, points out the role of the central executive for the coordination of two tasks in a dual-task situation. Yee, Laden, and Hunt (1994) propose a separate capacity to coordinate information from different sources (e.g., visual and verbal), and linked this concept to the central executive. These notions of coordination are not identical with the coordination of elements into structures as defined above. Dual-task coordination and information source coordination can be regarded as aspects of the supervisory function.

common basis on a higher level. Without such a positive intercorrelation of all subconstructs, we would have no reason to subsume them under the unitary concept of working memory.

3. Working memory functions and their components

The systematic construction of tasks according to a facet matrix has a further advantage: We can attempt to isolate theoretically meaningful components in the variance associated with a task. If task A′ differs from a baseline task A on a single, theoretically interesting dimension (e.g., a processing requirement added to a short-term storage task), then the residual of A′ after partialing out A can be assumed to represent variance that is related to this difference (e.g., variance associated with the added processing requirement).

One goal of the present study is to analyze the variance of typical working memory tasks by subtracting or partialing out baseline tasks. One of the functions in the facet model, supervision, can only be measured in this way, because every task that requires supervision also requires some basic process that is supervised, and the basic process will contribute to overall task performance. Besides this, the construct *simultaneous storage and processing* immediately suggests itself for a decomposition into variance associated with a storage component and variance associated with a processing component. In addition, one could assume that storage and processing have to be coordinated with each other in a dual-task combination, and this might require the supervision function (Baddeley, 1996; Baddeley & Della Sala, 1996). A typical storage and processing task might therefore represent a mixture of three underlying sources of variance: storage capacity, processing efficiency, and supervisory ability. Likewise, tasks that require coordination of elements into structures often require storage of the elements in addition to the construction of new relations among them (Oberauer et al., 2000). By contrasting coordination tasks with and without memory demand, we can potentially isolate the coordination and the storage component.

4. Method

4.1. Participants

We tested 135 students of different subjects from the University of Mannheim who received 80 DM (about US$50) for participation. Their mean age was 25.8 years (S.D. = 3.8), and 44% were female. Two participants were excluded from analysis due to missing data.

4.2. Design and materials

In order to measure the categories hypothesized by our facet taxonomy, we constructed new working memory tasks. Task construction was guided by the following principles: (1) Each task should measure specifically one function and one content domain. In the ideal case, performance should depend exclusively on one cognitive function paired with one content domain. (2) Tasks that operationalize different cells of the taxonomy should vary only in the feature that distinguishes the categories, that is, the function requirement and/or the content domain. We tried to accomplish this by designing a limited number of prototypic tasks that were then varied to fit the requirements of different categories. (3) It should be possible to obtain multiple independent measurements from each individual in order to estimate reliabilities on the level of single tasks (cf. Wittmann, 1988).

Not all of these requirements could be met fully. In particular, tasks measuring the same function over different content domains could be designed as variations over a common basic schema, but tasks measuring different functions could not always be constructed in this way. Moreover, the measurement of some functions is hardly possible without the contribution of others. Supervision, for example, can take place only when there are basic cognitive processes to be supervised; task performance will then depend on the efficiency of the basic and the supervising processes conjointly. Our strategy to deal with this problem was to measure task components separately, where possible. This gave us the opportunity to subtract or partial out unwanted variance from the performance scores and thereby isolate the variance components that we are interested in.

In addition to the working memory tasks, a new test for the Berlin Intelligence Structure model (Jäger, Süß, & Beauducel, 1997) was used to measure intelligence. The present paper is concerned only with the structure of working memory; the relationship between working memory and intelligence will be analyzed in a separate article (Süß, Oberauer, Wilhelm, & Wittmann, in preparation).

The tasks developed to measure single components (like processing) and their composites (like storage + processing) are summarized in Table 1. Within this schema, the three hypothesized functions of working memory were operationalized as follows: Simultaneous storage and processing was measured by serial recall performance in dual-task combinations of processing and storage. Coordination was measured both by tasks that require coordination of visible stimuli and by tasks requiring coordination of memorized information. The comparison of these two indicators should reveal whether the storage component makes a difference or whether the coordination function is reflected equally in memory-based tasks and in purely attentional tasks. Supervision was operationalized by the proportional increase of reaction times for processing with supervision, relative to tasks with the same processing demand without supervision.

The verbal–numerical content domain was covered by one numerical and one verbal task within each functional category. For the spatial domain, two tasks with visuo-spatial material were constructed. All stimulus materials were presented by computer, and responses were given either through the keyboard or on an answer sheet, depending on the task. If not stated otherwise below, there were 2 practice items and 15 test items for each task, and the test items were presented in ascending order of complexity (i.e., number of task elements).

4.2.1. Storage tasks

Measures for the short-term storage of information were traditional span tasks with digits and words for the verbal–numerical content domain. Word span used frequent German nouns, none of them longer than 12 letters, arranged into lists with a minimum of semantic

Table 1
Facet taxonomy for working memory tasks

Functional category	Components	Verbal	Numerical	Spatial 1	Spatial 2
	Storage	Word span	Digit span	Dot span	Pattern span
	Processing	(a) CRT categories	(a) CRT odd even	(a) CRT arrows up–down	(a) CRT patterns parts
		(b) CRT syllables	(b) CRT high low	(b) CRT arrows above–below	(b) CRT patterns symmetry
Storage and processing	Storage + processing	Word span (dual)	Digit span (dual)	Dot span (dual)	Pattern span (dual)
Coordination	Coordination	Monitoring verbal (no-memory)	Monitoring numerical (no-memory)	Flight control (no-memory)	Finding squares (no-memory)
Coordination	Coordination + storage	Monitoring verbal (memory)	Monitoring numerical (memory)	Flight control (memory)	Finding squares (memory)
Supervision	Processing + supervision	Switching (a)+(b)	Switching (a)+(b)	Switching (a)+(b)	Switching (a)+(b)

The first column represents the functional category of the proposed working memory structure model. The second column represents the hypothesized components involved in the tasks. CRT = choice reaction time task.

associations between the words. The words were presented sequentially at a rate of one per second in the center of the screen. After two practice trials, three test items of each list length between 4 and 8 were presented in increasing order. Participants attempted to reproduce each list by writing down the words into appropriate slots on the answer sheet. There was no time limit for recall. Digit span was identical to word span except that digits instead of words were presented; the digits were reproduced by typing them in correct order, and the computer provided feedback after each item. List lengths increased from 5 to 9.

For the visuo-spatial domain, we constructed two analogous span tasks. Dot span used spatial locations as material. A series of dots was presented for 1 s per dot, each in 1 of 25 possible locations within a square frame. Participants attempted to reproduce the dot positions in correct order by placing mouseclicks as close as possible to the original positions. They received feedback after each item. List lengths varied from 3 to 7; there were three items per list length. Pattern span presented a series of partially filled 3×3 matrices similar to those used by Bethell-Fox and Shepard (1988). Each pattern was shown for 3 s. The series was reproduced by marking the corresponding cells in empty matrices on the answer sheet. There were five items each for the list lengths 3–5. Unfortunately, data from 80 participants were lost for digit span and dot span due to a program error, so that most analyses rest on the remaining two span tasks only.

4.2.2. Processing tasks

The eight tasks in the second row of Table 1 were binary choice reaction time tasks (CRTs). The two tasks within the same column used the same type of stimulus but differed in the decision criterion. For each trial, the stimulus appeared in a rectangular frame in the middle of the screen. Participants were asked to respond as quickly as possible without errors by pressing one of two keys. For this purpose, the labels “right” and “left” were attached to the “x” and “<” keys on the German keyboard. Each participant received the same pseudorandom sequence of stimuli. The tasks were organized into five blocks of 16 trials each, following a practice block of 15 trials. Feedback was given after each block. Scores were built by aggregating the log-transformed reaction times within blocks after elimination of false responses, times below 200 ms, and times exceeding the individual’s mean by three standard deviations.

Verbal CRTs used nouns as stimuli. *CRT categories* required a semantic classification into animal versus plant terms, *CRT syllables* a syntactical classification according to the number of syllables (one or two). Numerical CRTs used three-digit numbers as material. *CRT odd–even* required an odd–even decision, *CRT large–small* a decision whether the number is larger or smaller than 500. The first two spatial CRTs used arrows as stimuli that appeared at varying locations within the frame and pointed to varying directions. For *CRT up–down*, participants had to react to the direction in which an arrow pointed (up or down). For *CRT above–below*, they had to base their decision on the location of the arrow (upper or lower half of the frame). Unclear cases were avoided by restricting arrow locations and directions to lie within clearly distinguishable ranges. The remaining two spatial tasks worked with partially filled 3×3 matrices that had to be classified as being symmetrical or not (*CRT symmetry*) or as consisting of either one or two separated parts (*CRT parts*). Patterns of two parts were defined as those where two filled surfaces existed that were not connected by a common edge.

4.2.3. Storage and processing tasks

Dual-task combinations of one storage and one processing task were designed to operationalize simultaneous storage and processing. The general task schema was as follows: First, the materials to be remembered were presented simultaneously for a limited time. Then participants were required to perform a series of CRTs that used material from the same content domain, but were unrelated to the memory task. The CRTs lasted for 5 s, regardless of how many trials a participant accomplished in this time. Participants were then required to recall the memory set in the same way as in the simple storage tasks. A fixed amount of time for the CRTs was chosen to hold the time between learning and recall constant for all participants, independent of their processing speed.

The numerical dual task combined digit span with *CRT odd–even*. Memory load varied from four to eight digits; there were three items with each memory load. The dual task with verbal material was constructed from word span together with *CRT categories*. Memory demand increased from 3 to 7. The first spatial variant, dot span (dual), consisted of a dot span task combined with *CRT pattern symmetry*. The second spatial task, named pattern span (dual), combined pattern span with *CRT arrows up–down*. Both dot span (dual) and pattern span (dual) had memory loads of 2, 3, and 4, each level represented by five items.

Two scores were obtained from each dual-task combination: one for the memory performance (number of elements recalled correctly), and one for the CRT subtask (log-transformed reaction times). Since the correlations between the two subtask scores were low, and since it is common practice to evaluate storage and processing tasks according to memory performance only (e.g., Daneman & Carpenter, 1980), we based our analyses only on the memory score from the dual tasks except where stated differently.

4.2.4. Coordination tasks

Coordination was measured by monitoring tasks. Participants had to watch several independently changing objects and monitor the changing relations between them. Certain critical relations had to be detected. These tasks require simultaneous access to several independent objects in order to compute and continuously update their relations. Each task was implemented in a no-memory version, where all the objects were continuously visible on the screen, and a memory version, where all or a subset of the objects had to be memorized.

The verbal coordination task (no-memory version) presented a 3×3 matrix with a word in each of the nine cells. Every 2 s, one randomly chosen word was replaced by a new word. Participants had to press the space bar whenever three rhyming words stood in a row, either horizontally or vertically or along a diagonal. Each item lasted for about 10 to 20 replacement cycles during which two to five target rows appeared. Consecutive target rows were separated by at least two intervening cycles. Numerical coordination was operationalized by the same type of task, only that three-digit numbers were presented in the cells, and participants watched out for rows of numbers with equal last digits. A number was replaced every 1.5 s. Feedback about hits, misses, and false alarms was presented after each item. In the memory conditions, each word or number was presented only for 2 s and then removed. Participants had to remember the elements that last appeared in each cell of the matrix. To adapt task difficulty, the number of cells was reduced. The verbal task used five cells arranged in a cross, so that only two rows of three elements had to be monitored. The numerical task consisted of 10 items with the cross arrangement and five items with a square arrangement of eight cells (the full 3×3 matrix minus the central cell), leaving four rows of three elements.

The first spatial coordination task, flight control, was constructed in analogy to a situation awareness task (Gugerty, 1997). Participants watched a number of airplanes, represented by small triangles that moved across the screen in various directions and with four different speeds. Airplanes appeared unpredictably on the border of the screen and maintained their direction of flight until they left the screen. Mountains were represented on the screen by clusters of brown squares. Participants had to take care that no planes were lost through crashes either with other planes or with mountains. They could stop the air traffic by pressing the space bar, then redirect one airplane chosen by mouseclick, and start movements again by pressing space once more. Participants started each item with 100 credit points, and the instructions explained that each lost plane would cost 10 points, and each stop of the traffic would cost 3 points. Their goal was to retain as many points as possible, and in addition, to keep the time during which the movements were stopped as short as possible. One item lasted about 12 s when run without interruptions. Feedback was given after each item about the number of crashes, the remaining points, and the cumulative time of the breaks. The number of airplanes simultaneously on the screen ranged from five to nine over the 15 items. In the memory version of flight control, the mountains appeared only for 5 s before the airplanes started, and had to be memorized from thereon. There were again 15 items, number of airplanes ranged from three to seven.

The second spatial coordination task, finding squares, presented 8–12 red dots placed at random in a 10×10 grid. Every 1.5 s, two of the dots jumped into a new position. Participants had to press the space bar whenever four of the dots formed a square, regardless of the square's size and position. In the memory version of finding squares, participants observed a sequence of 6–10 dots distributed over the 10×10 matrix. Each dot was visible for 1 s. After the sequence, participants had to decide whether any four of the dots had formed a square if they had been on the screen simultaneously. Since this was a binary decision with 50% guessing probability, we presented 20 items to increase the task's reliability.

Scores for the verbal and numerical monitoring tasks were hits minus false alarms. The same score was also built for the no-memory version of finding squares, whereas the memory version had to be scored simply as correct (1) versus wrong (0). For the flight control tasks, the number of crashes was taken as performance score.

4.2.5. Supervision tasks

Supervision was measured by four set-switching tasks constructed along the schema of Rogers and Monsell (1995). The two CRT tasks using the same kind of stimulus material were combined in a way that participants had to switch from one decision criterion to the other every second trial. Specifically, each stimulus appeared in one of the four cells of a 2×2 matrix, and the instructions specified that the first decision criterion had to be applied in the two upper cells, whereas the second criterion had to be applied in the two lower cells. For example, if a number appeared in the upper left cell, participants had to decide whether it was odd or even and press a key accordingly. If a number appeared in the bottom left cell, they had to decide whether the number was larger or smaller than 500. Successive stimuli appeared in adjacent cells, shifting from cell to cell in a regular clockwise order. Therefore, a switch from one decision criterion (“task set”) to the other was required every two trials. This design provides 50% switch trials (i.e., those immediately following a task set switch) and 50% no-switch trials within the switching task itself (cf. Rogers & Monsell, 1995). Following one practice block, six test blocks with 16 trials each were administered for each of the four switching tasks.

The switching tasks, together with the CRTs from which they were constructed, allowed us to derive two indicators of executive processes: (1) *Specific switching costs*, defined as the difference between the log-transformed switching and no-switching reaction times within the switching task, and (2) *general switching costs*, defined as the difference between log-transformed no-switching RTs and baseline RTs from the two single CRTs.[2] Kray and Lindenberger (2000) found that general switching costs were more affected by aging than specific switching costs. Salthouse, Fristoe, McGuthry, and Hambrick (1998) found the opposite pattern: Specific switching costs were related to age, but general switching costs were not. Since aging is strongly associated with a reduction of working memory capacity (Mayr & Kliegl, 1993; Salthouse, 1994), these findings led us to expect that general switching costs or specific switching costs (or both) are related to other working memory variables.

4.2.6. Working memory marker tasks

In order to validate the new tasks, we employed six working memory tasks from a previous study (Oberauer et al., 2000). Three of them (reading span, computation span, and numerical memory updating) had high loadings on a verbal–numerical factor, the other three (spatial short-term memory, spatial coordination, and the short-term memory version of spatial memory updating) loaded highly on a spatial factor. The six tasks were judged from task analysis to place demands on simultaneous storage and processing and on coordination, most of them requiring a mixture of both. For details of the tasks, we refer the reader to Oberauer et al. (2000).

4.3. Procedure

Participants were tested in groups of about 10 in the departmental computer pool. Each participant took part in two sessions of 4.5 h each, separated by 2–4 weeks. Each session consisted of four blocks separated by short breaks. A block started with three to five working memory tasks, followed by about the same number of intelligence test tasks. The working

[2] Differences between log-transformed times are equivalent to ratios. Hale and Jansen (1994) have shown that slow and fast individuals are related to each other by a constant proportion of each other’s reaction time over different tasks. This suggests that processing speed as an ability construct with some generality should best be measured on a proportional scale.

memory tasks were scheduled in a way that minimized problems with the comprehension of instructions: Switching followed immediately after the corresponding single CRTs, dual tasks followed after the corresponding single storage task, and the two coordination task versions (no-memory and memory) also followed each other.

5. Results

We present the results in two steps. First, the facet model of working memory is tested. Second, we report on our attempts to decompose the working memory functions into components. For all statistical tests, the alpha level was set to .05.

Table 2 summarizes descriptive data on the new tasks. The reliability was acceptable, with the exception of finding squares (memory) and the numerical monitoring task (no-memory). As a consequence of these reliability problems, and because the memory and no-memory versions of the coordination tasks were highly correlated, we aggregated the two versions of each coordination task for the structural analyses presented in this section. The resulting reliability estimates are added in parenthesis in Table 2. For the correlational analyses, all reaction times were log-transformed and multiplied with -1 such that positive values reflect better performance; all variables were converted into z-scores. The full correlation matrix of all variables is available at our webpage: http://www.psychologie.uni-mennheim.de/psycho2.

5.1. The structure of working memory

Twelve variables were selected to represent the three working memory functions, crossed with the two contents: The four specific switching-cost indicators were selected to operationalize supervision. The scores of the four coordination tasks were aggregated over the memory and the no-memory condition to form reliable indicators of coordination capacity. The four memory scores from the dual tasks represented the function of simultaneous storage and processing. Each function was represented by one verbal, one numerical, and two spatial tasks, so that there were two variables for each cell of the hypothesized facet matrix.

A measurement model with five factors was fit to the covariance matrix; three factors represented the functional categories, and two factors the content categories. Each variable had free loadings on one functional and one content factor. The initial model had an excellent fit with $\chi^2(38) = 42.0$ and CFI=.990. We found, however, that several loadings on the content factors were nonsignificant. Therefore, we tested simplifications of the model that omitted the content factors. The most parsimonious model that gave an adequate description of the data was accepted as Model 1, which is shown in Fig. 1. The fit of Model 1, $\chi^2(49) = 53.02$ and CFI=.984, was not significantly worse than that of the original five factor model ($\Delta\chi^2 = 13.02$, $df = 13$, P=.29).

We tested analogous models with general instead of specific switching costs as the indicators for the supervision function. Again, the original five factor model had an excellent fit with $\chi^2(38) = 36.64$ and CFI = 1.0. Several loadings on the content factors were near zero, and so we tested simplified versions of the model. The most parsimonious account of the data

Table 2
Descriptive statistics of working memory tasks

Function Category	Task	Mean (S.D.)	Cronbach's α
Processing	CRT categories	703 (171)	.964
	CRT syllables	638 (160)	.970
	CRT odd even	554 (84)	.937
	CRT large small	507 (59)	.941
	CRT up down	468 (60)	.933
	CRT above below	431 (64)	.923
	CRT symmetry	825 (236)	.931
	CRT parts	673 (116)	.957
Supervision (Model 1)	Specific SC verbal	246 (186)	.783
	Specific SC numerical	332 (198)	.794
	Specific SC arrows	299 (205)	.835
	Specific SC pattern	247 (252)	.768
Supervision (Model 2)	General SC verbal	241 (175)	.828
	General SC numerical	102 (97)	.832
	General SC arrows	145 (120)	.794
	General SC pattern	23 (93)	.656
Storage	Word span	3.9 (0.8)	.831
	Digit span	5.3 (1.0)	.818
	Dot span	2.6 (0.7)	.815
	Pattern span	2.4 (0.6)	.864
Storage + processing (Models 1 and 2)	Dual task verbal	3.6 (0.7)	.886
	Dual task numerical	5.1 (0.6)	.831
	Dual task dots	1.6 (0.6)	.859
	Dual task patterns	2.2 (0.4)	.913
Coordination (Models 1 and 2)	Monitoring verbal	1.4 (0.7)	.759 (.95)
	Monitoring numerical	1.7 (0.5)	.593 (.77)
	Flight control	1.0 (0.5)	.858 (.89)
	Finding squares	1.3 (0.7)	.725 (.70)
Coordination + storage (Models 1 and 2)	Monitoring verbal (memory)	0.9 (0.7)	.753 (.95)
	Monitoring numerical (memory)	1.3 (0.6)	.753 (.77)
	Flight control (memory)	0.8 (0.3)	.759 (.89)
	Finding squares (memory)	0.7 (0.1)	.279 (.70)
WM markers	Reading span	4.0 (1.1)	.877
	Computation span	5.6 (0.9)	.852
	Spatial STM	2.7 (0.3)	.703
	Spatial coordination	2.4 (0.6)	.734
	Memory updating spatial	1.7 (0.5)	.777
	Memory updating numerical	1.8 (0.5)	.819

SC = switch costs. Means and S.D. are given for untransformed times in milliseconds for CRT, time differences for switching variables, mean raw scores for the other tasks; Cronbach's alpha always refers to the scores used in the analyses (i.e., log-transformed RTs for the reaction time tasks), except for the coordination tasks wherein memory and no-memory tasks were aggregated (Cronbach's alpha after aggregation is given in parentheses).

with a reasonable fit was achieved with a five-factor model where the supervision variables had zero loadings on the content factors, $\chi^2(42) = 41.8$, CFI = 1.0. The χ^2 difference to the original model was not significant. This model (Model 2) is presented in Fig. 2. A three-factor

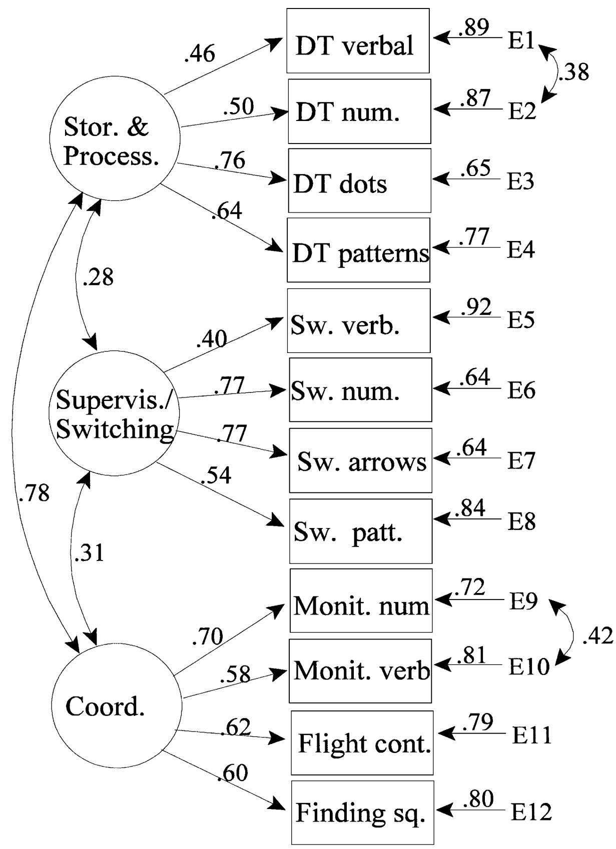

Fig. 1. Model 1: Measurement model for the tasks representing the facet matrix of working memory, with specific switching costs as indicators for supervision. DT = dual task (storage performance). Sw = specific switching costs.

model analogous to that shown in Fig. 1, in contrast, led to a significant reduction in fit relative to the original model, $\Delta\chi^2(13) = 30.7$, P=.003.

Our expectation that the general switching costs indicators from the switching tasks would correlate more with other working memory tasks than the specific switching costs was not met. Both indicators from the switching task seem to share only a small amount of variance with storage and processing as well as with coordination. The factors for simultaneous storage and processing and for coordination were strongly related in Model 1 (as well as in Model 2); nonetheless, they could not be fused into one factor. Fixing their correlation to one led to a dramatic decrease of fit, $\Delta\chi^2(1) = 45.65$. We conclude that simultaneous storage and processing and coordination of elements into structures are distinct, although highly related constructs.

Base on these models, we built six composites for further analysis. The z-standardized variables loading on each of the three factors in Model 1 were aggregated to form variables for storage and processing, supervision (specific switching costs), and coordination, respectively. In addition, a second supervision variable was composed from the four general switching cost indicators (used in Model 2). Two content-related variables were also built:

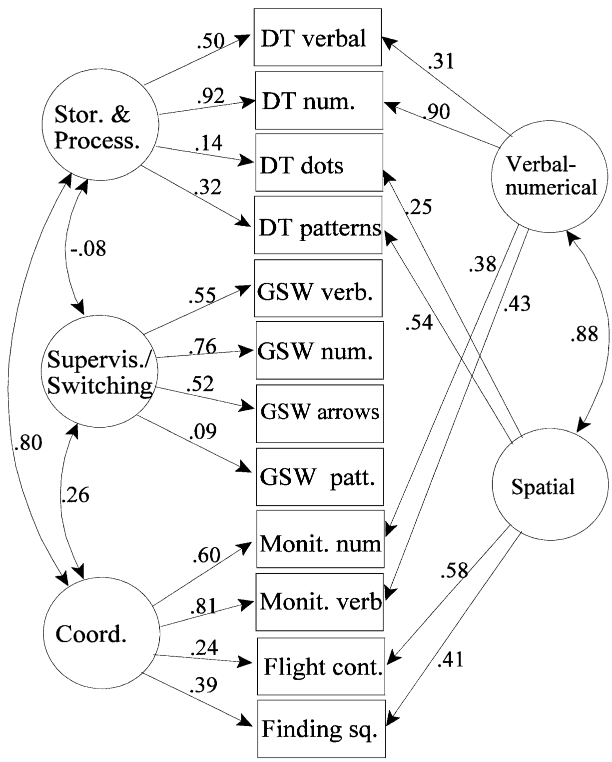

Fig. 2. Model 2: Measurement model for the tasks representing the facet matrix of working memory, with general switching costs (GSW) as indicators for supervision. Errors were omitted from the figure for clarity. No error intercorrelations were admitted.

The storage (dual) scores and the coordination tasks with verbal and numerical material were aggregated to form a verbal–numerical working memory variable, and the corresponding tasks with spatial contents were aggregated into a spatial composite. The resulting six variables were correlated with the six working memory marker tasks (Table 3).

The first thing to note is that the storage (dual), as well as the coordination composite, was highly correlated with the marker tasks. This suggests that the new working memory tasks measured the intended constructs, because the marker tasks had been constructed to operationalize simultaneous storage and processing (reading span, computation span, memory updating) or coordination (spatial STM, spatial coordination). The indicators for the supervision function, on the other hand, were only weakly related to the marker tasks. Since the marker tasks were not constructed to measure the supervisory function, this does not undermine the validity of the switching parameters as measures for supervision. It would be desirable, however, to have some convergent validation for these measures as well. Table 3 also shows a tendency for the verbal and numerical marker tasks to be more closely related to the verbal–numerical composite, and the spatial markers to be correlated more with the spatial composite.

Overall, these results confirm that the new tasks measured the constructs they were designed to measure. There is some ambiguity left, however, with respect to the indicators of

Table 3
Correlation of functional and content composites with working memory markers

	Storage (dual)	Coordination	Supervision (specific switching costs)	Supervision (general switching costs)	Verbal–numerical	Spatial
Reading span (VN)	.60*	.36*	.15	.10	.68*	.34*
Computation span (VN)	.57*	.20*	.10	−.01	.52*	.31*
Spatial STM (Spat)	.52*	.50*	.14	.18*	.48*	.58*
Spatial coordination (Spat)	.58*	.60*	.08	−.07	.55*	.66*
MU numerical (VN)	.62*	.59*	.21*	.03	.61*	.63*
MU spatial (Spat)	.64*	.56*	.17	.22*	.63*	.62*

MU = Memory updating. $N = 133$. (VN) = variable loaded on a verbal–numerical factor, (Spat) = variable loaded on a spatial factor in Oberauer et al. (2000).

* Significant with $P < .05$.

supervision; we will return to this issue in the context of our attempts to decompose the functional categories of the facet taxonomy into more fine-grained components of variance.

5.2. *Components of working memory functions*

5.2.1. *Storage and processing*

When he characterize a working memory function as "simultaneous storage and processing," the question arises whether this combined function is just the sum of the two more basic ones: The ability to memorize new material for a short time and the ability to process information quickly and efficiently. Alternatively, the combination of the two functions could itself require a third cognitive function, namely, the ability to coordinate or to integrate two partial tasks performed simultaneously. This ability should be associated with systematic variance in dual-task performance that cannot be accounted for by single-task performance.

As a first test of this hypothesis, we constructed two measurement models, one for the processing and one for the storage function. Both models incorporated the four single tasks and the corresponding scores from the dual tasks. The two groups of variables represented the same type of task, the only difference being that once the task is performed alone, once together with a second task. If this difference makes a difference with respect to the systematic variance in the scores, then a single-factor measurement model will not fit the data. To obtain a better fit, a second factor will be needed that accounts for the specific variance shared only by the dual-task conditions.

The processing speed model, presented in Fig. 3, was based on the eight single CRT variables and the four reaction time scores from the dual tasks. The two single-task CRTs within each cell of Table 1 were aggregated, because they used the same stimulus material, and we did not want to inflate the correlations within the single CRTs artificially due to identical materials. The two-factor model fit the data reasonably well with $\chi^2(12) = 23.59$ and CFI=.982. All four CRTs from the dual tasks had significant loadings on the specific factor, indicating that there is substantial common variance in these variables that cannot be

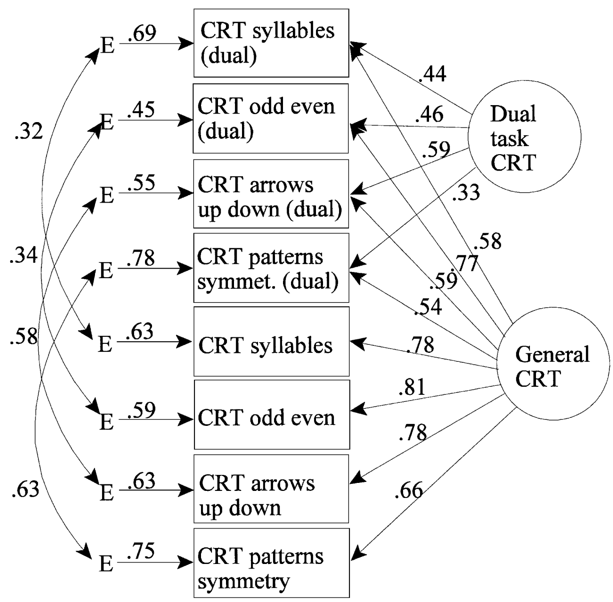

Fig. 3. Speed model: Four variables represent choice reaction time under single-task conditions, and four variables represent choice reaction time under dual-task conditions. Errors of tasks with the same stimulus material were free to correlate with each other to account for task-specific variance.

accounted for by general choice reaction time. Eliminating the specific factor led to a dramatic decrease of fit, $\Delta\chi^2(4) = 75.3$.[3] We conclude the CRTs in single- and in dual-task conditions measure similar, but not identical, aspects of processing speed.

For comparison, we also tested a speed model with two content-related factors, one for verbal and numerical speed tasks, the other for spatial speed tasks. Instead of differentiation on the functional dimension (single- vs. dual-task condition), this model separates the variance on the content dimension (verbal–numerical vs. spatial). The content factor model proved to be unacceptable with $\chi^2(15) = 95.6$ and CFI=.878.

For the storage tasks, an equivalent analysis was computed. Because complete data for all four span tasks were available for only 53 participants, this model is based on $N = 53$.[4] Fig. 4 shows the model with two factors, one representing the common variance of all span tasks, the other representing the specific variance of the same span tasks under dual-task conditions. This model fit the data quite well, $\chi^2(12) = 24.40$, CFI=.940. After eliminating the specific factor, the fit dropped to $\chi^2(16) = 38.04$; the difference was highly significant. Again, the

[3] A model where the factor intercorrelation is fixed to unity is equivalent to a single-factor model, only that it is a nested variant of the original two-factor model, so that statistical comparisons are possible.

[4] Such a small N usually prohibits structural equation modelling, because the chance to detect significant deviations from the model depends on the number of subjects, and accepting a model means to accept the null hypothesis. In the present case, however, our main intention is not to accept a model, but to reject the single-factor model. This means to reject the null hypothesis that the two models are equivalent. Since the $\Delta\chi^2$ test also depends on N, the small number of subjects actually works against our hypothesis.

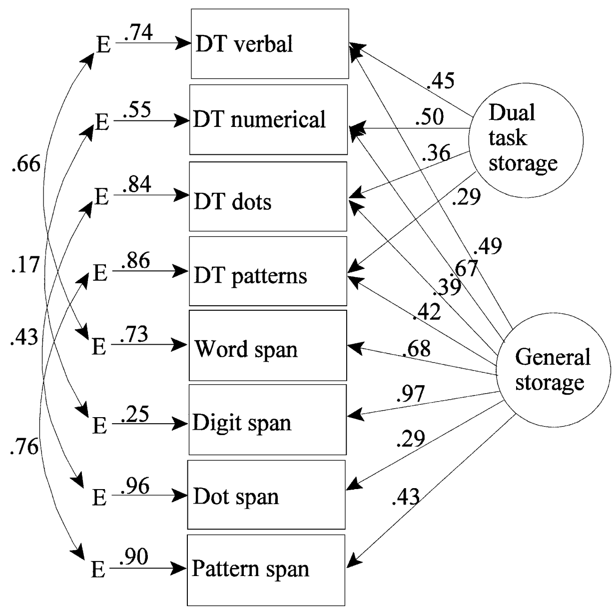

Fig. 4. Storage model: Four variables represent simple span tasks with different materials, the other four variables represent the same span tasks under dual-task condition. Errors of tasks with the same material were correlated freely to account for task-specific variance.

dual-task variables apparently measure something systematic over and above the variance they share with the single tasks. We also tested a model with two content factors for the span tasks. This model was worse than the functional two-factor model, $\chi^2(15) = 37.2$, CFI=.892, and does not even fit better than the single-factor model (P of $\Delta\chi^2$=.36).

It should be noted that storage accuracy and processing speed were not highly correlated with each other, neither under single- nor dual-task conditions. The correlations between scores of the storage and the processing subtasks from the same dual task were r=.30, .17, .20, and .23, for word span (dual), digit span (dual), dot span (dual), and pattern span (dual), respectively. The corresponding figures for the single tasks were r=.34, .31, .09, and .12. Given such low correlations between the subtasks, it is hardly justified to subsume the two scores from the dual tasks in our study under a single construct "simultaneous storage and processing." Storage and processing in the context of a dual-task demand, however, seem to measure something beyond corresponding single tasks. The next natural step is to find out what this surplus variance consists of.

To this end, we regressed the memory scores from the dual tasks onto the corresponding single spans, and the reaction time scores from the dual tasks on the corresponding single CRTs. The variance specific to the dual-task condition should now be isolated in the residuals. Unfortunately, the residuals also contain considerable error variance. The correlation between residuals from different tasks can provide a first estimate of how much systematic and task-independent variance is found in them. Table 4 presents the correlations of the eight residuals defined above. The correlations among the CRT residuals, as well as

Table 4
Intercorrelations of residuals from dual tasks after partialing out single tasks

	CRT verbal	CRT numerical	CRT arrows	CRT patterns	Word span	Digit span	Dot span
CRT numerical	.49*						
CRT arrows	.43*	.53*					
CRT patterns	.37*	.28*	.45*				
Word span	−.01	−.01	−.03	−.02			
Digit span	−.14	.03	−.02	−.11	.43*		
Dot span	.01	−.25	−.12	−.13	.29*	.15	
Pattern span	.04	.09	−.26*	−.01	.23*	.37*	.09

$N = 133$, except for correlations involving digit span and dot span: $N = 53$.
* Significant with $P < 0.5$.

those among the memory residuals, were moderately positive and, in most cases, significant. Correlations of residuals across components (i.e., memory with CRT), on the other hand, were mostly around zero. We consider these results as encouraging first evidence for common systematic variance due to the specific requirement of dual-task conditions. The residual variance associated with dual-task requirements, however, is not a general factor that expresses itself in both performance indicators, as could be expected from a general ability for dual-task coordination (e.g., Baddeley & Della Sala, 1996). Rather, there seem to be two sources of variance associated with dual-task costs, one reflected in the memory residuals and another reflected in the reaction time residuals.

To learn more about the meaning of the dual-task residuals, we first aggregated them over task contents to increase reliability, and then correlated the composite residual with the remaining working memory indicators (excluding those that are not statistically independent variables). These correlations are summarized in the second and third column of Table 5. The two residual variance components showed clearly distinct correlational patterns: The residual

Table 5
Components of working memory and their correlates

	Dual task memory residual	Dual task speed residual	Coordination memory residual
DT speed residual	.07		
Coordination memory residual	.26*	.11	
CRT (single)	.25*	.30*	.21*
Storage (single)	.04	.13	.26*
Coordination (no-memory)	.21*	.09	.25*
Specific switching costs	.12	.25*	.08
General switching costs	.13	.40*	.01
Working memory markers	.50*	.16	.45*

All variables are composites of four z-standardized tasks (or their residuals) from the four content categories, except dual task memory residual and storage (single), which are composed of the word span and pattern span tasks only: and coordination memory residual, which consists of 3 tasks. $N = 133$.
* Significant with $P < 0.5$.

from the dual-task memory score was strongly related to the working memory marker tasks. The residual from the processing speed score, in contrast, was correlated with specific switching costs and even more with general switching costs. This finding is interesting because the general switching costs are computed as the difference between (log-transformed) reaction times in a single-task and a dual-task condition. The general switch costs probably reflect the requirement to hold a second, momentarily irrelevant task set in memory in addition to executing the relevant task set. The correlation between the RT residual and the general switching costs points toward common variance in these two dual-task situations. It is most plausibly interpreted as reflecting the ability to preserve efficient processing in the context of an additional unrelated memory load.

5.2.2. Coordination and storage

Coordination capacity was measured with and without a storage demand. Does the additional requirement to memorize the elements make a difference for what the task measures? We tested this with a further two-factor model analogous to the previous ones. This model, with a general coordination factor and a specific factor for coordination with memory demand, showed an excellent fit, $\chi^2(12) = 15.09$, CFI=.991. Eliminating the specific factor increased $\chi^2(16)$ to 24.6, which is significantly worse (P=.049). This suggests that coordination with memory demand has specific systematic variance. Only two loadings on the specific factor were significant, however, and it might be that this factor represents not more than common task variance of the two monitoring tasks. A model with two content factors (one verbal–numerical, one spatial) also fits the data quite well with $\chi^2(15) = 18.8$ and CFI=.989, significantly better than the model with a single general factor.

In terms of our proposed set of ability components, the two versions of coordination tasks differ in that one requires the storage component in addition to the coordination component. As an attempt to isolate this component, we regressed the memory version of each task on the corresponding no-memory version (except for finding squares, where the memory version was not reliable). The resulting residuals were only weakly correlated with each other (verbal–numerical: .38, verbal–spatial: .11, n.s., numerical–spatial: .17).

Nonetheless, we built a composite from the three residuals; its correlations with other working memory variables are presented in the last column of Table 5. The storage residual from the coordination tasks correlated moderately with the storage residual from the dual tasks, and the two residuals had a quite similar profile of correlations with the other variables. This is compatible with the notion that both residuals represent a storage component in the context of a second demand (either processing or coordination), but the size of their correlation leaves enough room for specific variance, even if we take into account that the residuals suffer from low reliability. Taken together, the evidence that coordination with memory demands is associated with theoretically interesting variance beyond that of general coordination capacity is scarce at best.

5.2.3. Processing and supervision

A decomposition of variance is necessarily implicated in the measurement of the supervision function. Variance associated with the task that is supervised must be removed.

As mentioned above, we did this in two ways with the switching tasks: (1) General switching costs were defined as the difference of the log-transformed reaction times from no-switching trials and the corresponding baseline CRTs. (2) Specific switching costs were defined as the difference between switching and no-switching trials. We assumed that these two variables measure something different from each other and from the baseline CRTs themselves. Now we present a formal test for this assumption.

A model with three factors was fit to three groups of reaction time variables: The baseline CRTs (aggregating pairs of tasks with the same material), the no-switching trials from the switching tasks, and the switching trials from the switching tasks. All 12 variables were free to load on the first factor, which represented general speed in CRTs. The second factor represented the common variance of the switching and the no-switching trials of the switching task, over and above the baseline variance. This factor, thus, reflects variance

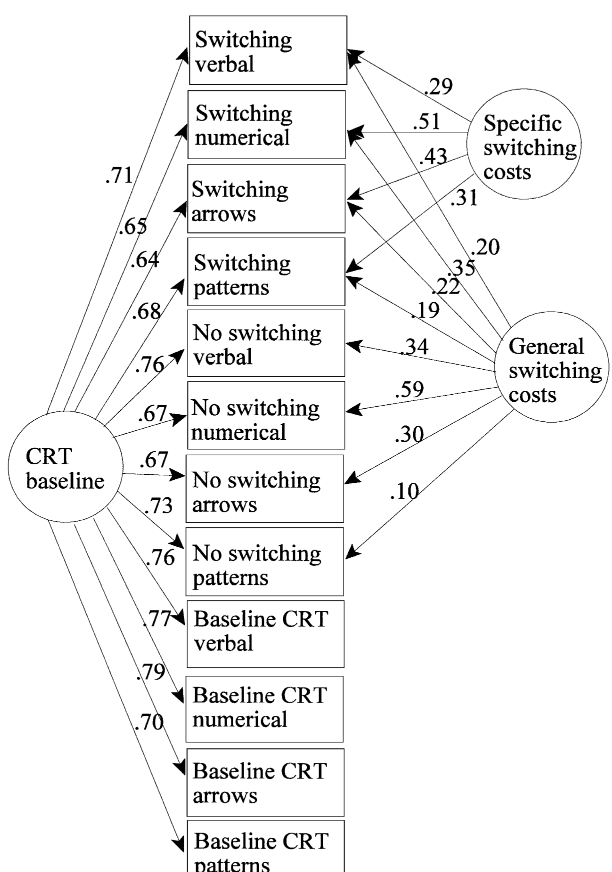

Fig. 5. Speed and supervision model: Baseline choice reaction times, no-switching trials and switching trials from the set switching task. Errors of tasks with the same stimuli (e.g., CRT verbal, no-switching verbal, and switching verbal) were freely correlated. Errors and their correlations were omitted from the figure for clarity.

associated with general switching costs. Finally, a specific switching costs factor was defined by the residual common variance of the switching trials only.

The model, depicted in Fig. 5, had a fit well within the conventional limits of acceptability, $\chi^2(30) = 58.3$ and CFI=.979. All loadings except one (*no-switching patterns* on the general switching costs factor) were significant, indicating that each factor represented substantial unique variance shared among its variables. This was confirmed by testing simpler models. When we eliminated the specific switching costs factor, $\chi^2(34)$ increased to 83.5, a significant difference. Likewise, eliminating the general switching costs factor yielded a $\chi^2(38)$ of 87.2, which is also significantly worse than the original model. The treatment of specific switching costs and general switching costs as different from the baseline CRTs therefore seems justified, and the two indicators of supervision do not measure exactly the same.[5]

6. Discussion

The present study yielded two important results that will be discussed in turn. First, working memory can be differentiated along a functional dimension. Second, content-related subdivisions within working memory gained rather weak support.

6.1. Fractionating the functions of working memory

Over the last two decades, researchers have devoted much attention to the differentiation of working memory capacity along the content facet (e.g., Daneman & Tardif, 1987; Kyllonen, 1994; Shah & Miyake, 1996). Our study is the first, to our knowledge, to provide evidence from individual differences data that working memory capacity can be subdivided into different cognitive functions (see Miyake et al., 2000, for a similar approach to executive functions).

Based on the present results, we propose to analyze working memory on two levels. On the first level, we can distinguish three functions: simultaneous storage and processing, supervision, and coordination of elements into structures. On the second level, these functions can be decomposed into more fine-grained components of variance.

Regarding the first level, one source of concern might be that the distinction between storage and processing, coordination, and supervision is confounded with method variance. Storage and processing, as well as supervision, were measured by a single kind of task. There might be a common variance associated with this kind of task, although the material used varied widely over the four content-related versions. Common method variance, however, is not very likely for the coordination category, which was measured by three different kinds of task and nonetheless formed a single factor. Moreover, four out of the eight tasks forming the coordination factor had an additional storage demand, and still the coordination factor was

[5] We also computed residuals from regressions of no-switching RTs on baseline CRTs and from regressions of switching RTs on no-switching RTs. As can be expected, the residuals were practically identical with the difference scores we used as indicators for supervision in Models 1 and 2, respectively (all correlations >.92).

distinguished from the storage and processing factor. Moreover, variables representing storage and processing and variables representing coordination accounted for different parts of the variance in the intelligence scales (Süß et al., in preparation). Together, these findings make it very likely that the dissociation between storage and processing and coordination is not only due to differences in measurement methods.

The storage and processing function was strongly related to coordination. It seems reasonable, therefore, to see them as two aspects of the same overarching construct, working memory. In this view, the scope of working is broadened to include, besides short-term retention and transformation of information, the ability to form new relations between elements. Formation of new relations requires simultaneous access to the elements that figure as arguments in the relations (cf. Pylyshyn, 1994). The capacity to provide simultaneous access to several distinct information elements without fusing them into a single chunk might therefore underlie the ability to coordinate elements into new structures. Simultaneous access is certainly useful also for short-term memorization, and this overlap might explain why the storage and processing factor is highly correlated with the coordination factor.

On a second level of differentiation, simultaneous storage and processing appears to be composed of four components: The baseline abilities to retain information over a short time (storage) and to perform simple cognitive operations quickly (processing), plus the components that reflect unique variance of storage in the context of a concurrent processing task, and processing efficiency in the context of a concurrent storage demand. The two storage-related components are only weakly related to the two processing components, so that the characterization of a working memory function as "simultaneous storage and processing" is at least misleading. In practice, most researchers measured this function by scoring only the memory performance in a dual task (following the ground breaking work of Daneman & Carpenter, 1980), and we chose to follow this tradition. In light of the evidence presented here, we prefer to speak about *storage in the context of processing* rather than *storage and processing* as a function of working memory. The processing aspect should be treated separately and might be better subsumed under the global construct of mental speed.

Coordination ability, even without memory demand, shared considerable variance with other working memory tasks (i.e., storage and processing tasks and the marker tasks for working memory). This supports the idea that the coordination function is not only relevant for information preserved in short-term memory, but also for objects and events perceived at the moment. This moves the concept of working memory further away from the notion of memory for past events towards attention to the present. The idea that "working memory" does not necessarily imply memory in a narrow sense should not be surprising in light of extant models (e.g., Baddeley, 1993; Cowan, 1995; Lovett, Reder, & Lebiere, 1999), but the relationship between working memory tasks requiring short-term storage and comparable tasks that require only attention to the present has never before been explored systematically.

Supervision, as operationalized by the task set switching variables, was only weakly related to the other working memory functions. To the extent that switching reflects a function of the central executive in terms of Baddeley's (1986) model, this implies that at least some aspects of the central executive are not very central to working memory. Our result is in accordance with Miyake et al. (2000) who found little relationship between their mental set shifting factor and standard measures of working memory capacity like operation span and dual-task performance. This adds to findings from a previous study (Oberauer et al., 2000), where other indicators of the supervisory function (random generation and verbal fluency) were only moderately correlated with typical working memory marker tasks.

One plausible interpretation of the general switching costs variable is that it reflects the capacity to avoid interference from an irrelevant, though still active, task set. This capacity might depend on a general inhibitory mechanism that becomes less efficient in old age (Hasher & Zacks, 1988). Some support for the generality of the underlying capacity beyond the task set switching situation is provided by the correlation of general switching costs with the residual from the dual-task reaction times. These residuals could reflect the ability to inhibit potential intrusions from the memory load into the ongoing choice reactions. This interpretation is speculative, and more research is needed to find out whether general switching costs reflect just specific variance related to switching situations or a more general capacity. Whatever the underlying factor is that produces slowing in a switching situation relative to baseline reaction times, out results imply that it cannot be reduced to general working memory capacity.

6.2. Verbal versus spatial working memory?

The distinction between verbal (including numerical) and spatial working memory seems to be well established in the literature (Baddeley, 1986; Logie, 1995; Oberauer et al., 2000; Shah & Miyake, 1996; Smith & Jonides, 1997). The present study provides a particular strong test for the existence of content-related factors in working memory. The facet design allowed us to vary task content orthogonal to function, and also fairly independent of methods. Furthermore, we measured content-related abilities over a broad range of different functions, thereby testing the generality of content factors.

We did find evidence for a distinction along the content dimension in our data, but it was conspicuously weak. Content factors improved the fit of the working memory measurement Model 2, but not the quite similar Model 1. The more specialized models of selected functions consistently showed that functional differentiations improved the model’s fit more than equally parsimonious content differentiations did. Where content factors were identified, they were highly correlated. These findings are not compatible with a strong version of multiple resource theory where the two content domains have independent resources. They are better compatible with a model like Baddeley’s, where a central, content-independent system can be expected to contribute a fair amount of variance to most working memory tasks. The content-related parts of the variance can then be attributed to more peripheral “slave systems.” Alternatively, they can be attributed to specific skills for certain cognitive operations like, for example, scheduling of rehearsal of verbal material or chunking of spatial patterns.

6.3. Conclusions

Working memory should be characterized as a highly interrelated ensemble of cognitive functions. The most central ones are storage of information in the context of processing, and coordination of elements into new structures. Other functional components, such as fast processing of information and supervision of cognitive operations, are only loosely related to the two primary functions. Only a small part of the variance associated with working memory functions is specific to the verbal or the spatial domain.

Acknowledgements

This research was supported by grant Wi 1390/1-2 of the German Research Foundation (DFG). Ralf Schulze, Reinhold Kliegl, and Ulrich v. Hecker contributed helpful comments on earlier versions of this paper. We thank Susanne Weis, Susanne Schweickert, Regina Johann, Heiko Engelmann, and Nicolas Sander for their help in collecting the data and Markus Werz for programming part of the working memory task battery.

References

Baddeley, A. D. (1986). *Working memory.* Oxford: Clarendon Press.

Baddeley, A. D. (1993). Working memory or working attention? In A. Baddeley, & L. Weiskrantz (Eds.), *Attention: selection, awareness, and control.* (pp. 152–170). Oxford: Clarendon Press.

Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, *49A*, 5–28.

Baddeley, A. D., & Della Sala, S. (1996). Working memory and executive control. *Philosophical Transactions of the Royal Society of London*, *351*, 1397–1404.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *Recent advances in learning and motivation*, *vol. 8.* (pp. 47–90). New York: Academic Press.

Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 12–23.

Canter, D. (1985). *Facet theory.* Berlin: Springer.

Cowan, N. (1995). *Attention and memory: an integrated framework*. New York: Oxford University Press.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

Daneman, M., & Tardif, T. (1987). Working memory and reading skill re-examined. In M. Coltheart (Ed.), *Attention and performance*, *vol. 12.* (pp. 491–508). Hillsdale: LEA.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: toward a unified theory of cognitive development and aging. *Developmental Review*, *12*, 45–75.

Engle, R. W., Conway, A. R. A., Tuholski, S. W., & Shisler, R. J. (1995). A resource account of inhibition. *Psychological Science*, *6*, 122–125.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake, & P. Shah (Eds.), *Models of working memory.* (pp. 102–134). Cambridge: Cambridge University Press.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*, 211–245.

Gugerty, L. (1997). Situation awareness during driving: explicit and implicit knowledge in dynamic spatial memory. *Journal of Experimental Psychology: Applied*, *3*, 42–66.

Guttman, L. (1954). A new approach to factor analysis: the radex. In P. F. Lazarsfeld (Ed.), *Mathematical thinking in the social sciences.* (pp. 258–348). Glencoe: Free Press.

Hale, S., & Jansen, J. (1994). Global processing-time coefficients characterize individual and group differences in cognitive speed. *Psychological Science*, *5*, 384–389.

Halford, G., Wilson, W. H., & Phillips, S. (1998). Processing capacity defined by relational complexity: implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences*, *21*, 803–864.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: a review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation*, *vol. 22.* (pp. 193–225). New York: Academic Press.

Jäger, A. O., Süß, H.-M., & Beauducel, A. (1997). Test für das Berliner Intelligenz-Strukturmodell (BIS 4). Göttingen: Hogrefe.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review*, *99*, 122–149.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging*, *15*, 126–147.

Kyllonen, P. C. (1994). Aptitude testing inspired by information processing: a test of the four-sources model. *Journal of General Psychology*, *120*, 375–405.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity? *Intelligence*, *14*, 389–433.

Logie, R. H. (1995). *Visuo-spatial working memory.* Hove: LEA.

Lovett, M., Reder, L., & Lebiere, C. (1999). Modeling working memory in a unified architecture: an ACT-R perspective. In A. Miyake, & P. Shah (Eds.), *Models of working memory.* (pp. 135–182). Cambridge: Cambridge University Press.

Mayr, U., & Kliegl, R. (1993). Sequential and coordinative complexity: age-based processing limitations in figural transformations. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *19*, 1297–1320.

Meiran, N. (1996). The reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *22*, 1423–1442.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology*, *41*, 49–100.

Oberauer, K., Süß, H.-M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity—facets of a cognitive ability construct. *Personality and Individual Differences*, *29*, 1017–1045.

Pennington, B. F. (1994). The working memory function of the prefrontal cortices. In M. M. Haith, J. B. Benson, R. J. Roberts, & B. F. Pennington (Eds.), *The development of future oriented processes*. (pp. 243–289). Chicago: Chicago University Press.

Pylyshyn, Z. W. (1994). Some primitive mechanisms of spatial attention. *Cognition*, *50*, 363–384.

Robin, N., & Holyoak, K. J. (1995). Relational complexity and the function of prefrontal cortex. In Gazzaniga M. S. (Ed.), *The cognitive neurosciences*. Cambridge: MIT Press.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science*, *2*, 179–183.

Salthouse, T. A. (1994). The aging of working memory. *Neuropsychology*, *8*, 535–543.

Salthouse, T. A., Fristoe, N., McGuthry, K. E., & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychology and Aging*, *13*, 445–461.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: an individual differences approach. *Journal of Experimental Psychology: General*, *125*, 4–27.

Shallice, T. (1978). The dominant action system: an information-processing approach to consciousness. In K. S. Singer, & J. L. Singer (Eds.), *The stream of consciousness*. (pp. 505–158). Chichester: Wiley.

Smith, E. E., & Jonides, J. (1997). Working memory: a view from neuroimaging. *Cognitive Psychology*, *33*, 5–42.

Stuss, D. T., Eskes, G. A., & Foster, J. K. (1994). Experimental neuropsychological studies of frontal lobe functions. In F. Boller, & J. Grafman (Eds.), *Handbook of neuropsychology*, *vol. 9* (pp. 149–185). Amsterdam: Elsevier.

Süß, H.-M., Oberauer, K., Wilhelm, W., & Wittmann, W. W. (in preparation). The relationship between working-memory capacity and intelligence.

Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Mishkin, F. S., de Menezes Santos, M., Thomas, C. R., & Miller, B. L. (1999). A system for relational reasoning in human prefrontal cortex. *Psychological Science*, *10*, 119–125.

Wittmann, W. W. (1988). Multivariate reliability theory. Principles of symmetry and successful validation strategies. In J. R. Nesselroade, & A. R. B. (Ed.), *Handbook of multivariate experimental psychology* (pp. 505–560). New York: Plenum.

Yee, P. L., Laden, B., & Hunt, E. (1994). The coordination of compensatory tracking and anticipatory timing tasks. *Intelligence*, *18*, 259–287.